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CH-1211 Geneva 23
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Engineering Specification

D2 (MBRC) – DIPOLE COOLING SCHEME

Abstract

Superconducting beam separation dipoles of four different types are required in the Experimental Insertions (IR 1, 2, 5, and 8) and the RF Insertion (IR 4). The D2 twin aperture dipoles are among those utilized in the Experimental Insertions to bring the beams into collision. The D2 dipoles are cooled at 4.5 K. This specification establishes the requirements and interfaces for the cooling of the D2 dipoles.

Prepared by :	***Reviewed by :***	***Approved by :***
K. C. Wu BNL Kcwu@bnl.gov	**E. Willen** BNL Willen@bnl.gov **J. Strait** FNAL strait@fnal.gov	**T. Taylor** Tom.Taylor@cern.ch

History of Changes

Rev. No.	*Date*	*Pages*	*Description of Changes*
1.0	2001-04-27	All	Initial submission
1.1	2001-06-13	5	Added text to clarify the function of the small diameter heat shield supply/return line.
		7	Table 1: revised heat loads based on new calculations [4]. Static heat loads are the same for all four locations.
		8-10	Tables 2-5: revised cold mass length from 10.35 m to 10.40 m [3]. Used new heat load calculations [4].
		12-14	Figures 3-8: added CERN jumper interface piping convention on the flow diagrams.
		11, 15-17	Added CERN jumper interface piping convention to text and to Tables 8-10.
1.1	2001-07-13	All	Released version

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1. OVERVIEW

Superconducting beam separation dipoles of single aperture (MBX) with lattice designation D1 and twin aperture (MBRC) with lattice designation D2 are utilised in the Experimental Insertions [1]. They bring the two beams of the LHC, separated by 194 mm in the arcs, into collision at four separate points, then separate the beams again beyond the collision point.

This specification refers only to the D2 dipoles (MBRC) and their cryo-assemblies (LBRC).

1.1 LOCATION

Each superconducting D2 dipole cryo-assembly is a dual aperture, RHIC-type coil in a single cold mass [2]. D2 magnets are located on each side of IPs 1, 2, 5 and 8, for a total of eight, plus one spare. One side of one such region is shown in Figure 1.

The configurations of the eight D2 cryo-assemblies are identical, with the exception of a technical service module (QQS) attached to D2 [3]. One spare is built as a replacement for any of the eight installed units. The operation, piping and instrumentation take the necessary variations into account

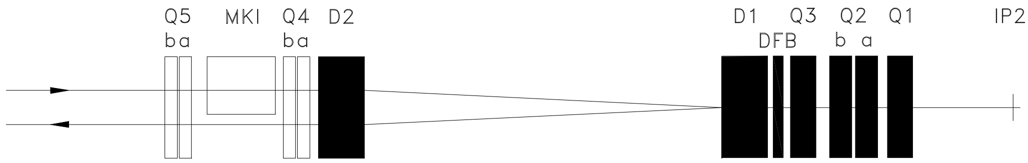

Figure 1 Geometry in Intersection Region 2 of the LHC. Dipole magnets D1 and D2 bring the beams into collision at IP2.

1.2 COOLING

The D2 and its neighboring Q4 magnet form one cryogenic module with a length of 20 meters. In the D2-Q4 module, each of the magnets, heat shields and the beam screens are cooled in series. Both magnets operate at 4.5K in two-phase helium. Although most of the LHC magnets have to be operated at a temperature of 1.9 K, the D2 magnets can easily provide the necessary field strength for the LHC when operated at 4.5 K. Therefore they have been designed to be operated at 4.5 K to minimize the use of 1.9 K resources.

The cooling scheme utilizes Headers C and D in the LHC cryogenic distribution line to provide a bath of liquid helium at 4.5 K. Header B is not used, which has the advantage of saving electric power in the LHC helium refrigeration system. The lowest temperature of this cooling scheme is 4.5 K due to the 1.3 bar operating pressure of the D Header. The present pool boiling cooling scheme has taken cryogenic module, tunnel slope, magnet geometry and liquid control into consideration. For pool boiling cooling, helium vapor must be vented from the high elevation end of the module. To provide suitable cooling for the long magnet during cooldown, the helium supply line is connected to the low elevation end opposite to the return line. Thus helium flows through the magnet in one direction during cooldown and warmup.

For steady state operation, liquid helium is fed into the high elevation end to prevent helium vapor, entrained during the Joule-Thomson expansion process, from entering the magnet cold mass. The amount of vapor in the cold mass is limited to that generated from heat in the magnet. The superconducting coil and bus are kept immersed in liquid helium by controlling the liquid level in the end volume of the cold mass.

Beam screens are used to reduce the dynamic heat load to the beam tube and coil. Their use reduces the 4.5 K heat load and the vapor flow inside the magnet cold mass. The beam screens will be provided and installed by CERN.

Two technical service modules, one in each end of the D2-Q4 module, connect the cryogenic module to the LHC distribution line. The purpose is to avoid using a single large connection.

2. CRYOSTAT LAYOUT

The cross sectional view of the LBRC cryo-assembly is shown in Figure 2. The MBRC cold mass, enclosed in an aluminum heat shield, is supported by three posts. These posts are identical to those used in the LHC arc dipole. There are four cold pipes in the cryostat. Only the two heat shield lines, E1/E2, are used for the LHC operation. The cold mass supply line are used for tests to be performed at BNL. There is no need to have a beam screen supply line running through the cryostat. The beam screen cooling flow is brought in at the Q4 end, passed down one aperture, turned around at the D2 end, returned back through the other aperture, and taken out at the Q4 end.

- CL/LD is a cold mass supply line and is used for tests to be performed at BNL only. The inner diameter of these lines is about 5 cm.
- E1 and E2 are used to cool heat shield at 50 K. The inner diameter of these lines is 8 cm. A 15 mm inner diameter line is installed inside the shield return line to reduce thermal conduction between the heat shield supply side and return lines. The small diameter line merely lays in the bottom of the large diameter extrusion and make minimal thermal contact.

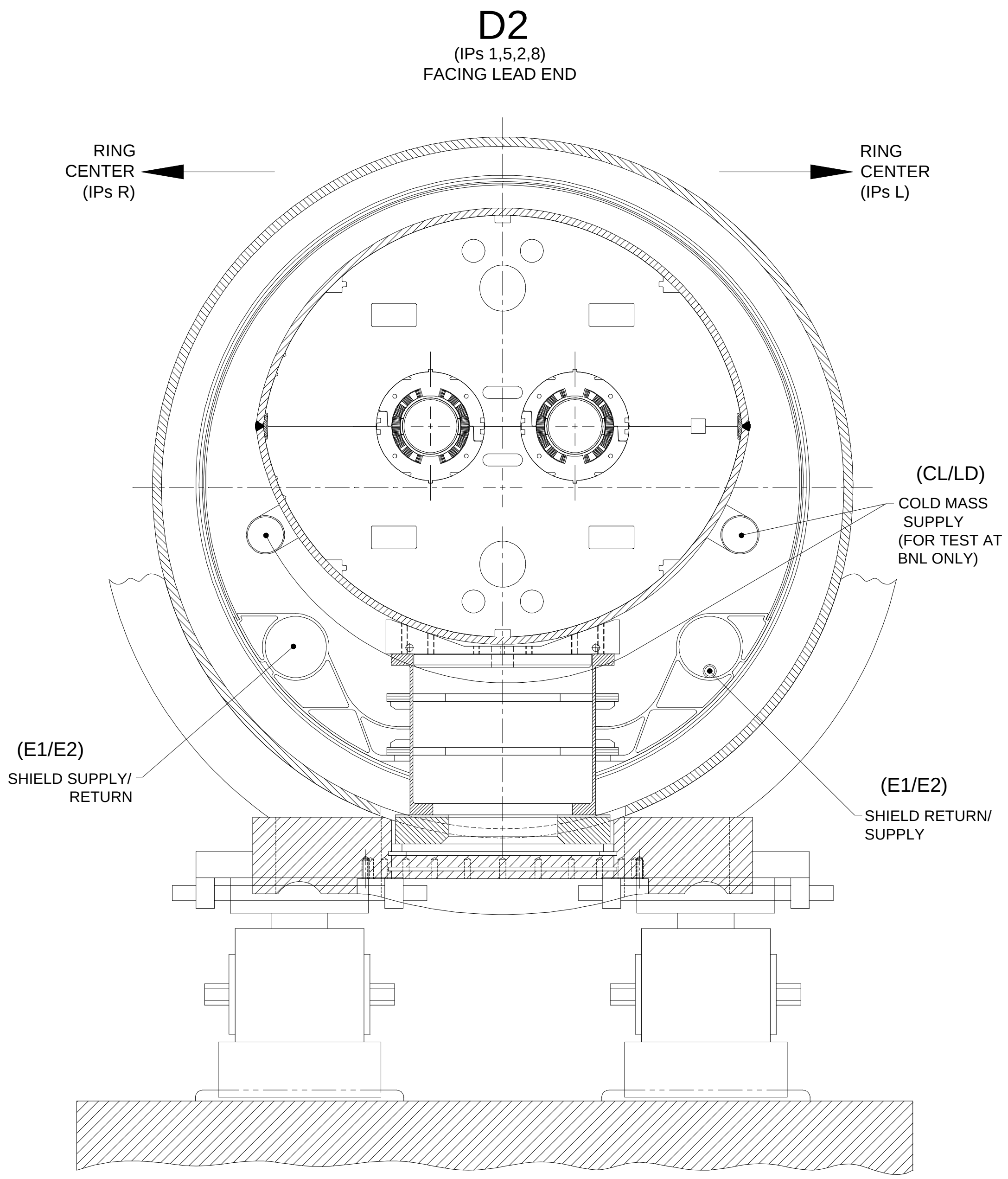

Figure 2 Sectional view of the LBRC (D2) cryo-assembly

3. COOLING

3.1 GENERAL REQUIREMENTS

Heat load is a key parameter for a cooling system. In LHC, the heat loads consist of two types, static and dynamic. The static heat load comes from conduction through the supports, and radiation past the thermal insulation of the cryostat. The dynamic heat load comes from machine operation. The dynamic heat load consists of synchrotron radiation, image currents, beam scattering, photoelectron effects and secondary particles. The beam screen, operated between 4.5 and 20 K, is used to prevent most of the dynamic heat load from entering the magnet. There are three temperature levels at which heat is removed from D2: 50-75 K in the thermal heat shield, 4.5-20 K in the beam screen and 4.5 K in the magnet cold mass.

3.1.1 STATIC HEAT LOADS

Static heat loads have been estimated by R. van Weelderen of CERN [4] and are given in Table 1. Heat loads for resistive heating due to electric splices, instrumentation feed through and cryogenic jumper lines are itemized.

Table 1 Design static heat load (Watts) for D2 magnet

Source	***Heat Shield*** 50-75 K	***Beam Screen*** 4.5-20 K	***Cold Mass*** 4.5 K
Supports	21.30	-	1.50
Thermal Shield	27.95	-	-
Radiation to cold mass	-	-	1.01
Resistive heating	0.01	-	0.31
Instrument feed	-	-	0.53
Cold to warm transition	13.00	-	2.32
QQS	3.70	-	0.09
½ jumper	0	-	0.27
Total	65.96	0	6.03

3.1.2 DYNAMIC HEAT LOADS

Dynamic heat load is developed inside the beam tube. It has no effect on the 50-75 K heat shield. The dynamic heat loads of D2 are estimated by CERN [4] for both the nominal and ultimate LHC operating conditions. There is a slight difference in dynamic heat load between IP1 and 5 and IP2 and 8. The dynamic heat loads in IP1/5, IP2 and IP8, are given in Tables 2, 3 and 4 respectively. The heat loads for synchrotron radiation, image current beam scattering, photoelectrons and secondary particles are given in watts per meter. The photoelectron heat input depends on whether the region has magnetic field. A total length of 10.40 m is used in the dynamic heat load calculation with 9.45 m of that assumed to be in the field region.

Table 2 Dynamic heat load of D2 in IP 1 and 5 at nominal and ulitmate operating conditions

Source	Nominal		Ultimate	
	Beam Screen 4.5 – 20 K	Cold Mass 4.5 K	Beam Screen 4.5 – 20 K	Cold Mass 4.5 K
Synchrotron radiation	0.016	0	0.024	0
Image Current (W/m)	0.192	0.005	0.438	0.011
Beam gas scattering (W/m)	0	0.050	0	0.050
Photoelectron[a]				
-field region (W/m)	0.070	0	0.240	0
-field free region (W/m)	0.603	0	2.070	0
Secondaries (W/m)	0	0.270	0	0.675
Total for 10.40 meter length	3.40	3.38	9.04	7.65

Note: (a) From the mechanical layout drawings [1], the field region is taken as the magnetic length 9.45m. The total length is taken as the cold mass length 10.40 m. The remaining length is taken as the field free region 0.95 m.

Table 3 Dynamic heat load of D2 in IP2 at nominal and ultimate operating conditions

Source	Nominal		Ultimate	
	Beam Screen 4.5 – 20 K	Cold Mass 4.5 K	Beam Screen 4.5 – 20 K	Cold Mass 4.5 K
Synchrotron radiation	0.020	0	0.030	0
Image Current (W/m)	0.192	0.005	0.438	0.011
Beam gas scattering (W/m)	0	0.050	0	0.050
Photoelectron[a]				
-field region (W/m)	0.077	0	0.260	0
-field free region (W/m)	0.663	0	2.280	0
Secondaries[b] (W/m)	0	0	0	0
Total for 10.40 meter length	3.56	0.57	9.49	0.63

Note (a): From the mechanical layout drawings [1], the field region is taken as the magnetic length 9.45m. The total length is taken as the cold mass length 10.40 m. The remaining length is taken as the field free region 0.95 m.

Note (b): Heat loads due to secondary particles at IP2 and IP8 do not change between nominal and ultimate luminosity cases, as the luminosity at these points is limited by the requirements of the experiments.

Table 4 Dynamic heat load of D2 in IP8 at nominal and ultimate operating conditions

Source	Nominal		Ultimate	
	Beam Screen 4.5 – 20 K	Cold Mass 4.5 K	Beam Screen 4.5 – 20 K	Cold Mass 4.5 K
Synchrotron radiation	0.020	0	0.030	0
Image Current (W/m)	0.192	0.005	0.438	0.011
Beam gas scattering (W/m)	0	0.050	0	0.050
Photoelectron[a]				
-field region (W/m)	0.077	0	0.260	0
-field free region (W/m)	0.663	0	2.280	0
Secondaries[b] (W/m)	0	1.051	0	1.051
Total for 10.40 meter length	3.56	11.50	9.40	11.56

Note: (a) From the mechanical layout drawings [1], the field region is taken as the magnetic length 9.45m. The total length is taken as the cold mass length 10.40 m. The remaining length is taken as the field free region 0.95 m.

Note: (b) Heat loads due to secondary particles at IP2 and IP8 do not change between nominal and ultimate luminosity cases, as the luminosity at these points is limited by the requirements of the experiments.

3.1.3 TOTAL HEAT LOADS

Total heat loads, equal to the sum of the static and dynamic heat loads, are given in Table 5. The cooling system is designed for the maximum expected heat load of D2 and Q4. Pressure and temperature at the 4.5 K supply line shall be 3 bar and 4.6 K. Pressure in the return line D shall not be greater than 1.3 bar.

Table 5 Total heat load (Watts) for the D2 magnets at nominal and ultimate luminosity

	Heat Shield 50-75 K	***Beam Screen 4.5-20 K***	***Cold Mass 4.5 K***
IP1 and IP5 – Nominal			
Static (Table 1)	66.0	0	6.0
Dynamic (Table 2)	0	3.4	3.4
Total	66.0	3.4	9.4
IP1 and IP5 – Ultimate			
Static (Table 1)	66.0	0	6.0
Dynamic (Table 2)	0	9.0	7.7
Total	66.0	9.0	13.7
IP2 – Nominal			
Static (Table 1)	66.0	0	6.0
Dynamic (Table 3)	0	3.6	0.6
Total	66.0	3.6	6.6
IP2 – Ultimate			
Static (Table 1)	66.0	0	6.0
Dynamic (Table 3)	0	9.5	0.6
Total	66.0	9.5	6.6
IP8 – Nominal			
Static (Table 1)	66.0	0	6.0
Dynamic (Table 4)	0	3.6	11.5
Total	66.0	3.6	17.5
IP8 – Ultimate			
Static (Table 1)	66.0	0	6.0
Dynamic (Table 4)	0	9.4	11.6
Total	66.0	9.4	17.6

3.2 COOLING SCHEME

The D2 and Q4 magnets are combined together in one cryogenic module [5]. The module is cooled by pool boiling of liquid helium at 4.5 K. The helium flows associated with pool boiling cooling are sensitive to the tunnel slope and the feed and return lines have been arranged to produce the correct flow directions. Table 6 provides the slopes and elevation changes in the D2-Q4 modules over the 20 m length. The cryogenic feed is located at the high elevation end of the module and is connected to the LHC distribution line through the technical service module QQS. The location of the supply and return lines are summarized in Table 7. To limit each QQS in size, two QQS are used, one on each end of the module, to accommodate all of the piping and valves.

The flow arrangements are divided into two categories depending on whether the slope is positive (IR 1, 2 and 8) or negative (IR 5). The flow schematics for the left and right sides of IR1, 2 and 8, and IR5 are given in Figures 3, 4, 5 and 6. A DFBM feed box for current leads of D2 and Q4 are also shown. The dashed box, around D2 including the QQS on the D2 side, indicates the responsibility of BNL. CL1 is the cooldown line, CL2 is the steady state liquid feed, LD is the vapor return, and E1/E2 are heat shield cooling. CFV, LCV and TCV are control valves for cooldown, steady state and flow respectively. In Figures 3 – 6, the CERN jumper interface piping convention are also shown for easy reference.

Table 6 Slopes and elevation changes for the 20 m long D2-Q4 module

Insertion Region	*Slope*	*Elevation Change*
IR 1	+1.23 %	+24.6 cm
IR 2	+1.39 %	+27.8 cm
IR 5	-1.24 %	-24.8 cm
IR 8	+0.36 %	+7.2 cm

Table 7 Location of Helium Supply and Return lines Lines for the D2-Q4 Module

Item	*Elevation*	*Left Side-IR1/2/8 And Right Side-IR5*	*Right Side -IR1/2/8 and Left Side-IR5*
Helium supply during cooldown	Low	Q4	D2
Helium return during cooldown	High	D2	Q4
Helium supply during operation	High	D2	Q4
Helium return during operation	High	D2	Q4

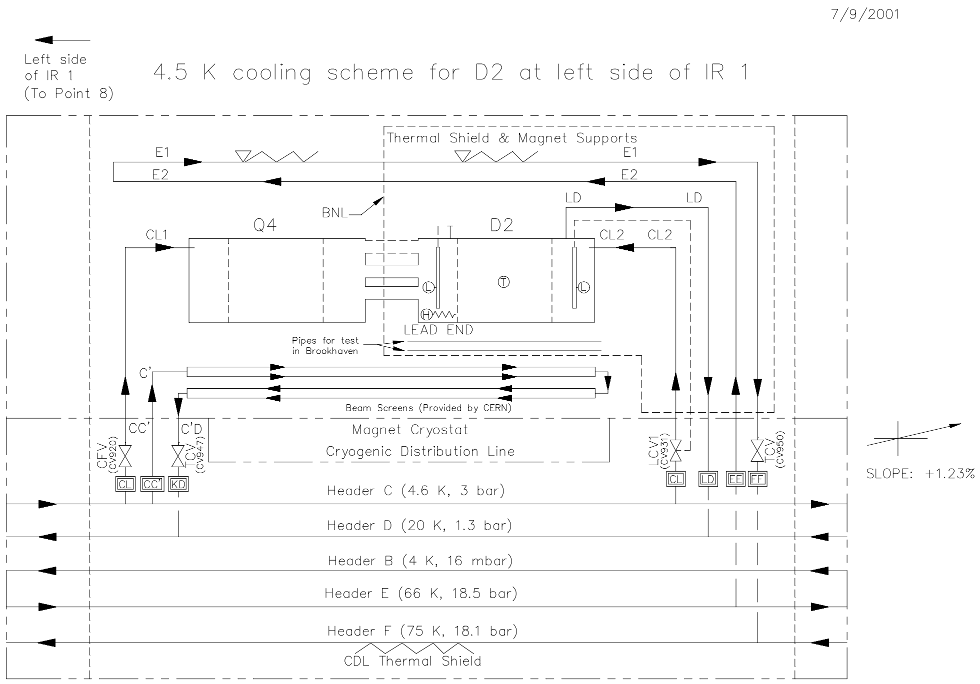

Figure 3   4.5 K cooling scheme for D2-Q4 at the left side of IR 1.

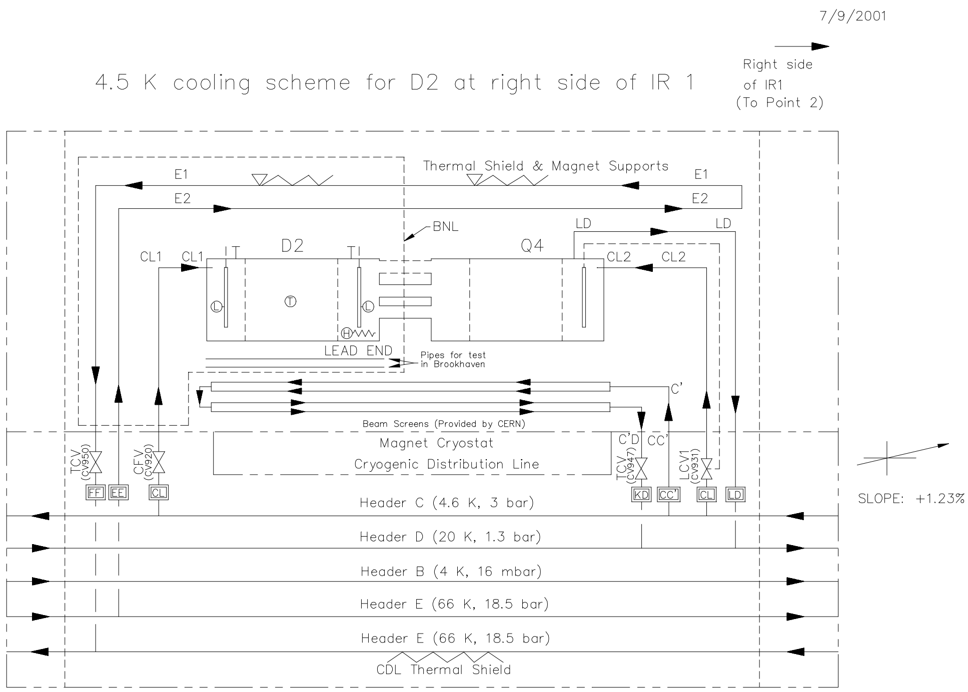

Figure 4   4.5 K cooling scheme for D2-Q4 at the right side of IR 1.

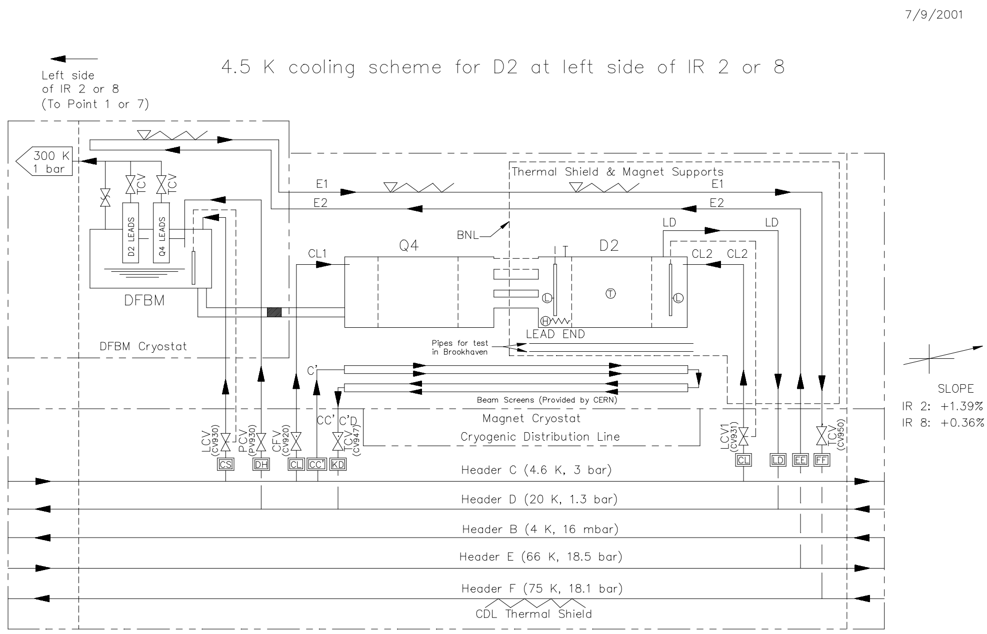

Figure 5 4.5 K cooling scheme for D2-Q4 at the left side of IR 2 and 8.

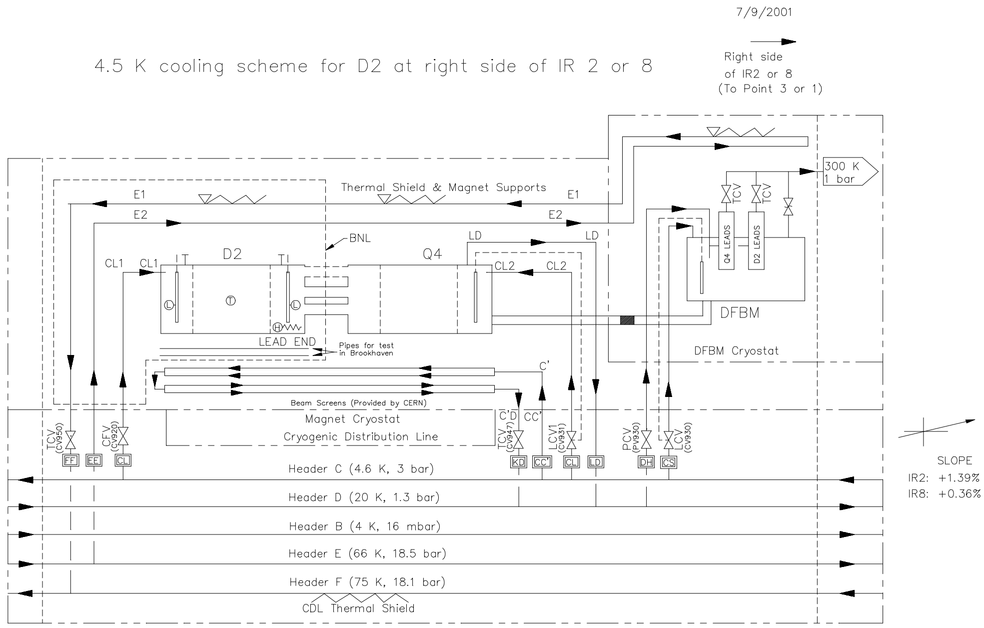

Figure 6 4.5 K cooling scheme for D2-Q4 at the right side of IR 2 and 8.

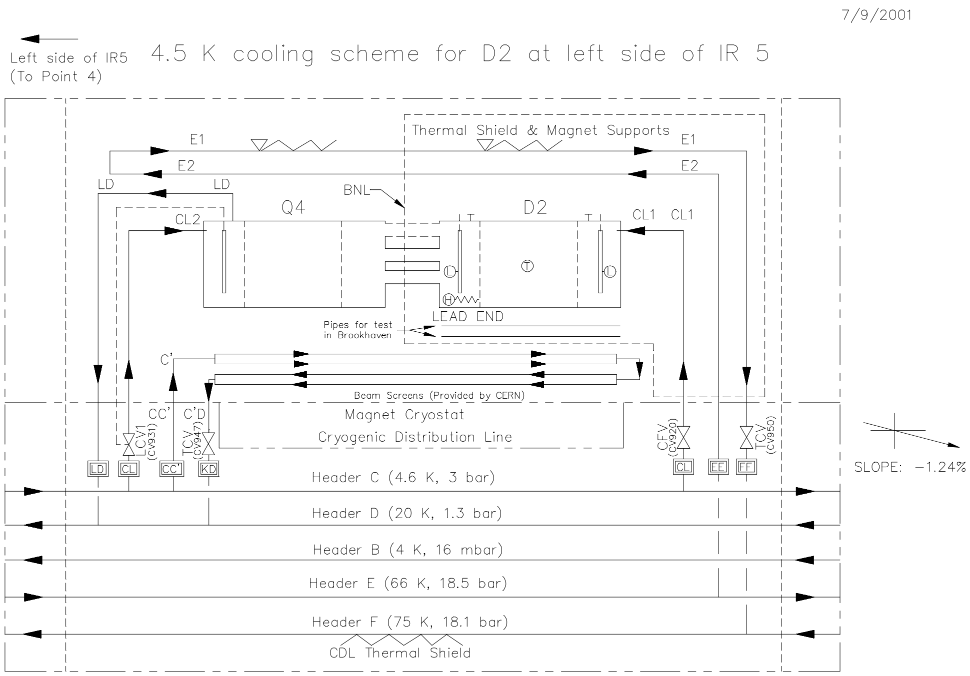

Figure 7 4.5 K cooling scheme for D2-Q4 at the left side of IR 5.

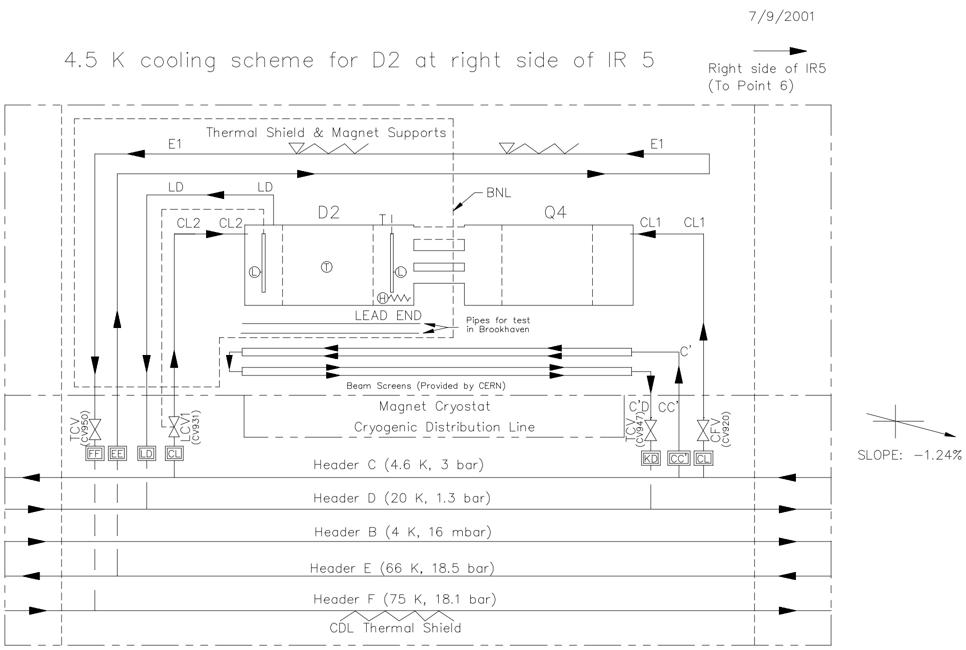

Figure 8 4.5 K cooling scheme for D2-Q4 at the right side of IR 5.

3.3 OPERATION AT 4.5 K

For the 4.5 K steady state operation, two phase helium from Header C is fed to the high elevation end of the D2-Q4 cryogenic module and returns as vapor from the same end. Liquid level is controlled by valves LCV1 [CV931]. The CERN convention is given inside the [ ]. The level gauges are installed in the end volume of the cold masses. A description of the helium flow in each location is given in Table 8.

Table 8 Description of 4.5 K cooling helium flow. The liquid level inside the D2-Q4 module is controlled by valve LCV1 [CV931].

Location	***Schematic***	***Helium Flow***
Left side of IR 1, 2, & 8 Right side of IR 5 (D2 is higher than Q4)	Figure 3 Figure 6	1. A liquid level gauge, installed in the end volume of the D2 cold mass, provides a control signal for valve LCV1 [CV931]. 2. Two phase helium from Header C is fed to the high elevation end of D2 through the CL2 line [CL]. 3. Helium vapor returns to Header D from the high elevation end of D2 through line LD [LD].
Right side of IR 1, 2, & 8 Left side of IR 5 (Q4 is higher than D2)	Figure 4 Figure 5	1. A liquid level gauge, installed in the end volume of the Q4 cold mass, provides a control signal for valve LCV1 [CV931]. 2. Two phase helium from Header C is fed to the high elevation end of Q4 through line CL2 [CL]. 3. Helium vapor returns to Header D from the high elevation end of Q4 through line LD [LD].

3.4 HEAT SHIELD COOLING

In the two QQS design, the shield flow enters from the QQS on the D2 side. Helium flows through the supply line to Q4 end of the module. Helium returns, cooling the heat shield, to the D2 side of the D2-Q4 module and then returns to the QQS. A description of the shield flow in each location is given in Table 9. The CERN convention is given inside the [ ].

Table 9 Helium flow to the heat shield. The shield temperature is controlled by control valve TCV [CV950].

Location	*Schematic*	*Helium Flow*
Left side of IR 1, 2, & 8 Right side of IR 5 (D2 is higher than Q4)	Figure 3 Figure 6	1. The shield flow enters the cryogenic module in the high elevation end of D2 through [EE] line. 2. It flows through the E2 line in D2-Q4 to the end of Q4 (and possibly to the DFBM). 3. The helium flow turns around through the E1 line to cool the heat shield. 4. Shield flow returns to the F Header in the D2 side through [FF] line.
Right side of IR 1, 2, & 8 Left side of IR 5 (Q4 is higher than D2)	Figure 4 Figure 5	1. The shield flow enters the cryogenic module in the low elevation end of D2 through [EE] line. 2. It flows through the E2 line in D2-Q4 to the end of Q4 (and possibly to the DFBM). 3. The helium flow turns around through the E1 line to cool the heat shield. 4. Shield flow returns to the F Header in the D2 side through [FF] line.

3.5 COOLDOWN FROM 300 K TO 4.5 K

For the cooldown from 300 K to 4.5 K, helium enters the D2-Q4 module from the low elevation end. It exits the module from the high elevation end. A description of the helium flow in each location is given in Table 10. The CERN convention is given inside the [ ].

Table 10 Helium flows during cooldown from 300 K to 4.5 K

Location	***Schematic***	***Helium Flow***
Left side of IR 1, 2, & 8 Right side of IR 5 (D2 is higher than Q4)	Figure 3 Figure 6	1. Helium from header C flows, through jumper line [CL], control valve CFV [CV920] and line CL1, to the low elevation end of Q4. 2. Helium flows through Q4 and into D2. 3. Helium returns to Header D from the high elevation end of D2 through the LD line [LD].
Right side of IR 1, 2, & 8 Left side of IR 5 (Q4 is higher than D2)	Figure 4 Figure 5	1. Helium from header C flows, through jumper line [CL], control valve CFV [CV920] and line CL1, to the low elevation end of D2. 2. Helium flows through D2 and into Q4. 3. Helium returns to Header D from the high elevation end of Q4 through the LD line [LD].

3.6 BEAM SCREEN COOLING

The beam screen cooling flow enters the D2-Q4 module from the QQS in the Q4 side, line CC' [CC']. It flows through two cooling passages inside one of the beam tubes to the non-lead end of D2. After cooling this beam tube, the helium flow turns around. It flows through two cooling passages in the 2nd beam tube toward Q4. The two beam tubes of D2-Q4 are cooled in series. The flow exits the D2-Q4 module from the same QQS in the Q4 side, line C'D [KD]. A temperature control valve, TCV [CV947], is used to maintain the screen below 20 K.

3.7 SAFETY RELIEF VALVES

No relief valve is allocated for the D2-Q4 cryogenic module. There is no valve between the beam screen and Header C in the LHC distribution line. The relief valve in Header C is used to vent helium in the 4.5-20 K cooling line. There is no valve between the D2-Q4 cold mass and Header D either. Two phase helium in the D2-Q4 cold mass will be vented to the Header D should the pressure build up. The 50-75 K cooling circuit of the D2-Q4 module is part of the LHC Sector heat shield which has relief valves to handle the venting capacity of the entire circuit. The vacuum vessel tank relief will be provided on the Q4 cryostat.

3.8 CONTROL VALVES

The control valves shown in Figures 3-6 are sized for design and cooldown conditions. Since the heat shield of D2 is in series with Q4, the required helium flow and control valve TCV is calculated from the total heat load of the D2-Q4 cryogenic module.

3.9 OTHER INSTRUMENTATION

For convenience of cryogenic operation, redundant temperature sensors will be installed in the middle of the D2 cold mass. An electric heater will be installed inside the end volume in the lead end of D2.

4. REFERENCES

1. "LAYOUT OF LHC INSERTIONS OPTICS LAYOUT VERSION 6.2", LHC Drawings LHCLSX_0001 and LHCLSX_0002 (IR1); LHCLSX_0003 and LHCLSX_0004 (IR2); LHCLSX_0009 and LHCLSX_0010 (IR5); LHCLSX_0015 and LHCLSX_0016 (IR8).
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4. Rob van Weelderen, Web publication, http://home.cern.ch/vanweeld/heatload/hlmagnets.html
5. Cooling Scheme for BNL-Built LHC Magnets, K. C. Wu, S. R. Plate, E. H. Willen, R. van Weelderen, R. Ostojic, presented in the 1999 Cryogenic Engineering Conference, Montreal, Canada.